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PB-260 196

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Robert A. Taft Sanitary Engineering Center, Cincinnati, Ohio

October 1967

1B001863
2-C-316
253165
PB 260 196
KEYWORD DOCUMENT
FWPCA, NW REGION

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U. S. DEPARTMENT OF THE INTERIOR
Federal Water Pollution Control Administration
Cincinnati Water Research Laboratory
Cincinnati, Ohio 45226
October, 1967

BIBLIOGRAPHIC DATA SHEET	1. Report No.	2.	3. Recipient's Accession No. PB-260 196
4. Title and Subtitle Reservoir Water Quality Control by Destratification			5. Report Date Oct 67 6.
7. Author(s) by James M. Symons, William H. Irwin, and Gordon G. Robeck.			8. Performing Organization Rept. No.
9. Performing Organization Name and Address Robert A. Taft Sanitary Engineering Center, Cincinnati, Ohio. Cincinnati Water Research Lab.			10. Project/Task/Work Unit No. 11. Contract/Grant No.
12. Sponsoring Organization Name and Address			13. Type of Report & Period Covered 14.

15. Supplementary Notes

16. Abstracts

The results of a study on the control of water quality in reservoirs by engineering methods is summarized. A lake in northern Kentucky, which normally stratifies thermall, was artificially destratified by bringing water from the bottom to the surface with a mechanical pump and later a diffused-air pump. Water quality analyses showed that the temperature of the lake became uniform with depth, dissolved oxygen was added to the water and reduced materials oxidized. Finally, algal populations on the surface were not increased by the destratification procedure.

17. Key Words and Document Analysis. 17a. Descriptors

17b. Identifiers/Open-Ended Terms

Reservoirs
*Water quality
Thermal stratification
*Destratification
Kentucky
Stream flow

17c. COSATI Field/Group 8H

18. Availability Statement	19. Security Class (This Report) UNCLASSIFIED	21. No. of Pages 29p
	20. Security Class (This Page UNCLASSIFIED	22. Price

RESERVOIR WATER QUALITY CONTROL BY DESTRATIFICATION

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ABSTRACT

This paper summarizes the results of a study on the control of water quality in reservoirs by engineering methods. During 1965 a 2,900 ac-ft lake in the northern part of the State of Kentucky, which normally stratifies thermally, was artificially destratified by bringing water from the bottom to the surface with a mechanical pump. The pump, mounted on a raft, was stationed over the deepest portion of the lake, and operated for 5 weeks during August and early September. Water quality analyses showed that the temperature of the lake became uniform with depth, dissolved oxygen (DO) was added to the water, and reduced materials were oxidized. Finally, algal populations on the surface were not increased by the destratification procedure.

In an attempt to reduce the energy required per unit volume for destratification, this same lake was artificially mixed in 1966 using a diffused-air pump. During the 1966 operation, the lake was mixed four times, for short intervals, beginning in June. Water quality measurements showed the same improvement in 1966 that occurred in 1965, and the diffused-air system seemed to have better performance and was easier to install and maintain.

KEY WORDS: WATER QUALITY, THERMAL STRATIFICATION, ARTIFICIAL DESTRATIFICATION, STREAMFLOW REGULATION, MECHANICAL PUMPING, DIFFUSED-AIR PUMPING

RESERVOIR WATER QUALITY CONTROL BY DESTRATIFICATION*

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INTRODUCTION

Streamflow regulation for water quality control, a scheme in which good quality stored water is released at times of low streamflow as a means of diluting and thereby improving water quality (Figure 1), has been under active consideration in the United States for several years. While reservoir releases have long been used to supplement mainstream water quantity, their specific use for quality control has been limited to date.

To be successful, any streamflow regulation scheme is predicated on the availability of good quality discharges from the storage impoundment. If poor quality water is discharged into the main stream, mainstream quality deteriorates and the water quality control scheme fails. Downstream quality, because of poor quality impoundment discharges, has been degraded in various locations in the United States and has been documented in two locations by Ingols[1,2] and Fish[3]. Thus, research in this area, originally by the U. S. Public Health Service and currently (1967) by the Federal Water Pollution Control Administration staff in Cincinnati, Ohio gave top priority to impoundment influences

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*To be published in the Jahrbuch Vom Wasser of 1967, Federal Republic of Germany.

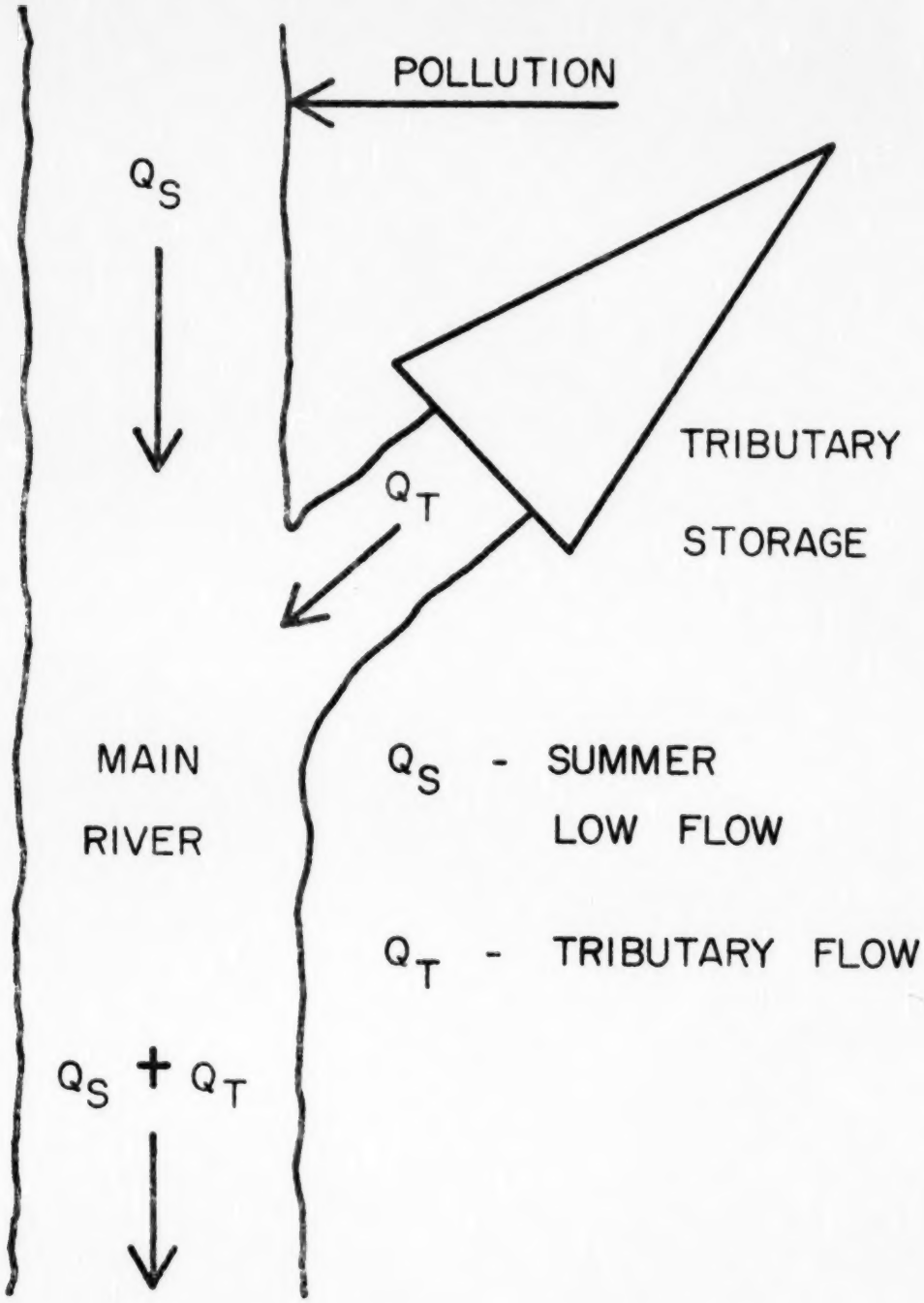


FIGURE 1. GENERAL SCHEME FOR STREAMFLOW REGULATION.

on water quality. This paper discusses in general terms the changes that may occur when a free-flowing stream is impounded, and summarizes the research work carried out by the U. S. Public Health Service and the Federal Water Pollution Control Administration on the control of reservoir water quality by engineering methods.

EFFECTS ON WATER QUALITY

Churchill[4], Love[5], and Woodward and LeBosquet[6] have detailed the possible beneficial and detrimental water quality effects that may be realized when a free-flowing stream is dammed. Beneficial effects include: 1) reduced turbidity because of low velocities and long detention times, 2) reduced hardness caused by algal production of carbon dioxide and subsequent precipitation of calcium carbonate, 3) reduced color and BOD caused by long detention times, permitting biodegradation, 4) reduction in coliform density caused by increased detention time, permitting natural die-off, and 5) equalizing action, smoothing high concentrations of various incoming pollutants.

Several detrimental effects that may occur when water is impounded include: 1) less mixing because reduced velocities may cause a waste that formerly was distributed throughout a stream to hug the shore line, 2) lower atmospheric reaeration caused by lower velocities and increased depth, 3) a backup of pollutants caused by a changing water surface profile, 4) increased algal problems, either in the form of aesthetically displeasing scums, or taste and odor in the water, both of which are caused by the increased detention time in reservoirs, 5) no bottom scour because of increased depth, and 6) thermal stratification.

The occurrence of thermal stratification is a major difference between streams and impoundments, and is one reason that the great backlog of information developed on stream behavior is not strictly applicable to reservoirs

and lakes. Thermal stratification has been thoroughly reviewed by Kittrell[7]; thus, only its effect on water quality shall be discussed here. Warm, light water lying over cold water acts as a lid on the system. This lid prevents the bottom, dense water from circulating to the surface. Under these conditions, the natural oxygen demand of this water will remove the dissolved oxygen (DO) from solution. When the DO concentration goes to zero in the dense water zone, several reactions take place. Under the anaerobic conditions, iron and manganese are reduced and go into solution; sulfates are reduced and odorous hydrogen sulfide is formed; excess carbon dioxide is created and the pH of the water is lowered; and aerobic biodegradation of organic materials ceases. All of these reactions are potentially detrimental to water quality; thus, when the bottom water of a stratified impoundment is released through power turbines, poor quality water may be discharged downstream.

RESULTS

Many of the water quality problems that develop during the storage of water are related to the onset of thermal stratification. This density-layering of water, as mentioned previously, often leads to the disappearance of dissolved oxygen in the lower portions of the impoundment. This anaerobic condition then permits several undesirable reactions to occur, producing poor quality water. Studies were begun to determine if artificial destratification of lakes and reservoirs could prevent these reactions, thereby maintaining good quality water vertically throughout the impoundment, during a summer season. A theoretical analysis showed that the work required to lift a unit volume of cold water to the surface in a stratified lake was quite small (Figure 2), and that during such an operation, favorable density currents would develop, so as to drain to the deepest portion of the reservoir all of the cold water initially present (Figure 3). Based on these favorable concepts, artificial destratification was attempted and the results are summarized below.

Artificial Destratification by Pumping

The first destratification method investigated was the mechanical pumping of cold water from the bottom of a stratified water body and discharging it at the surface. The apparatus used for this investigation is shown schematically in Figure 4. A 12-inch mixed-flow pump driven by a gasoline engine was suspended over the deepest part of the lake from an anchored raft. The suction line extended to within 1 or 2 feet of the bottom and drew water from this depth for discharge at the surface.

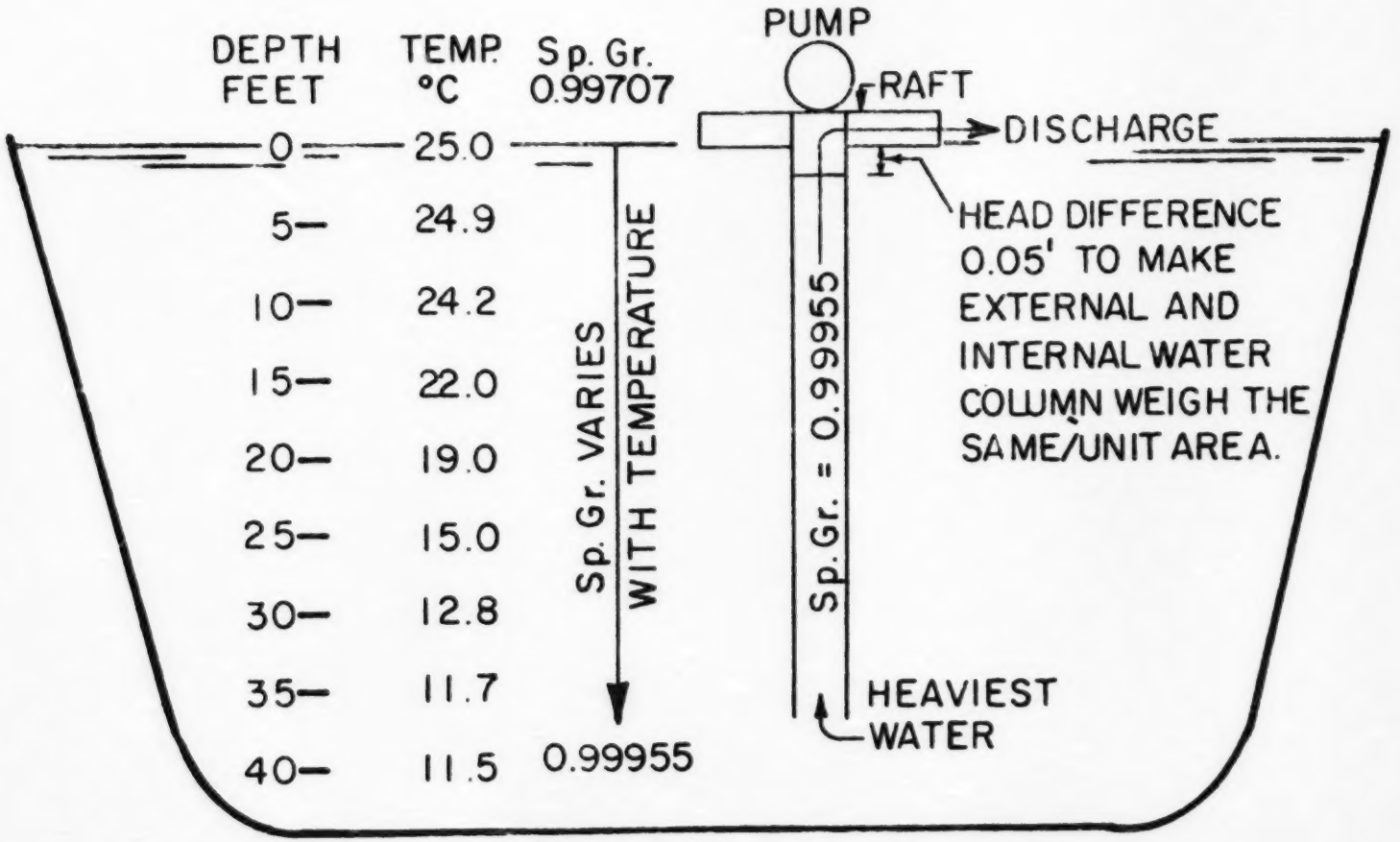


Figure 2. THEORETICAL ELEVATION HEAD TO LIFT BOTTOM WATER TO SURFACE-LAKE COWAN, OHIO

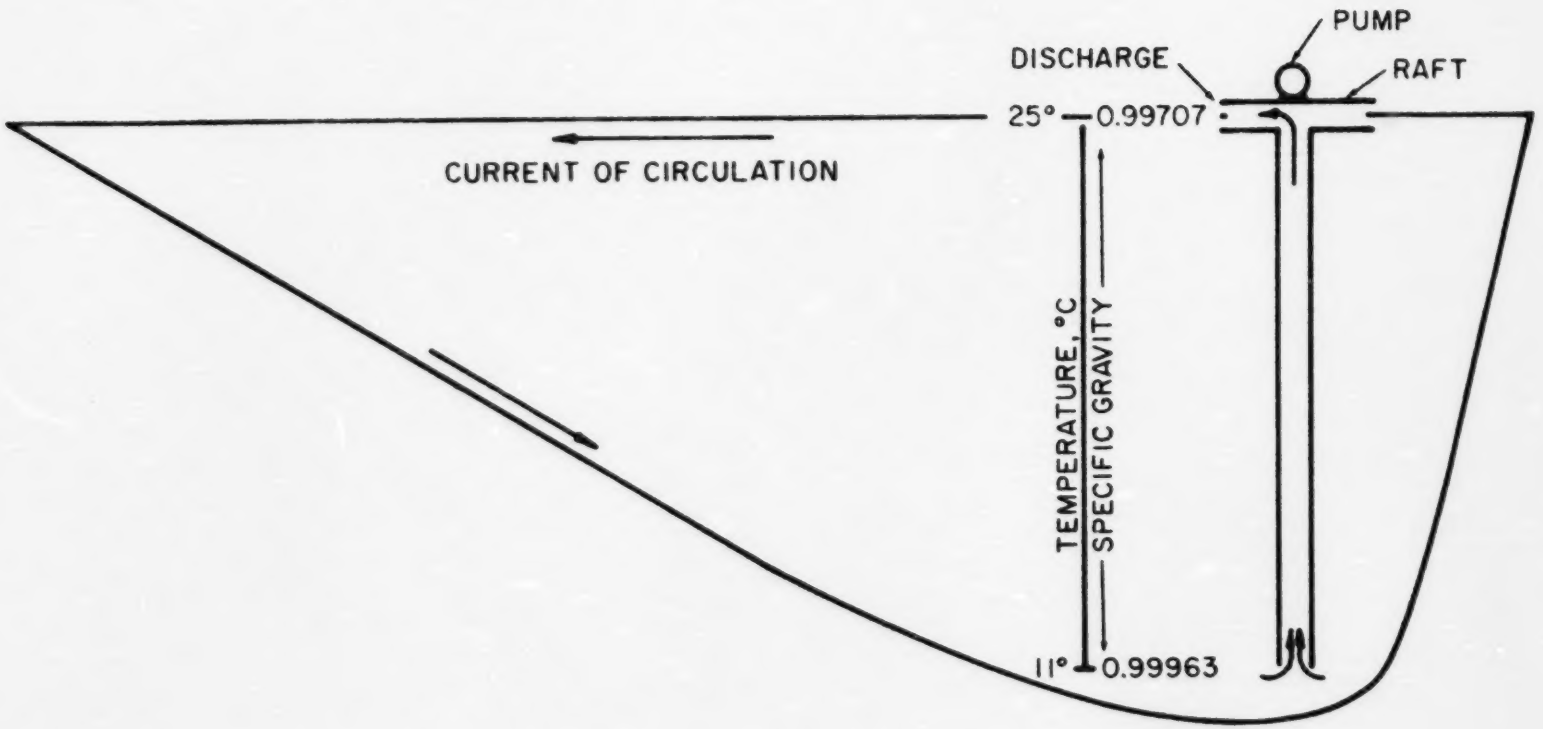


FIGURE 2. DENSITY VARIATION AND DESTRATIFICATION CURRENTS.

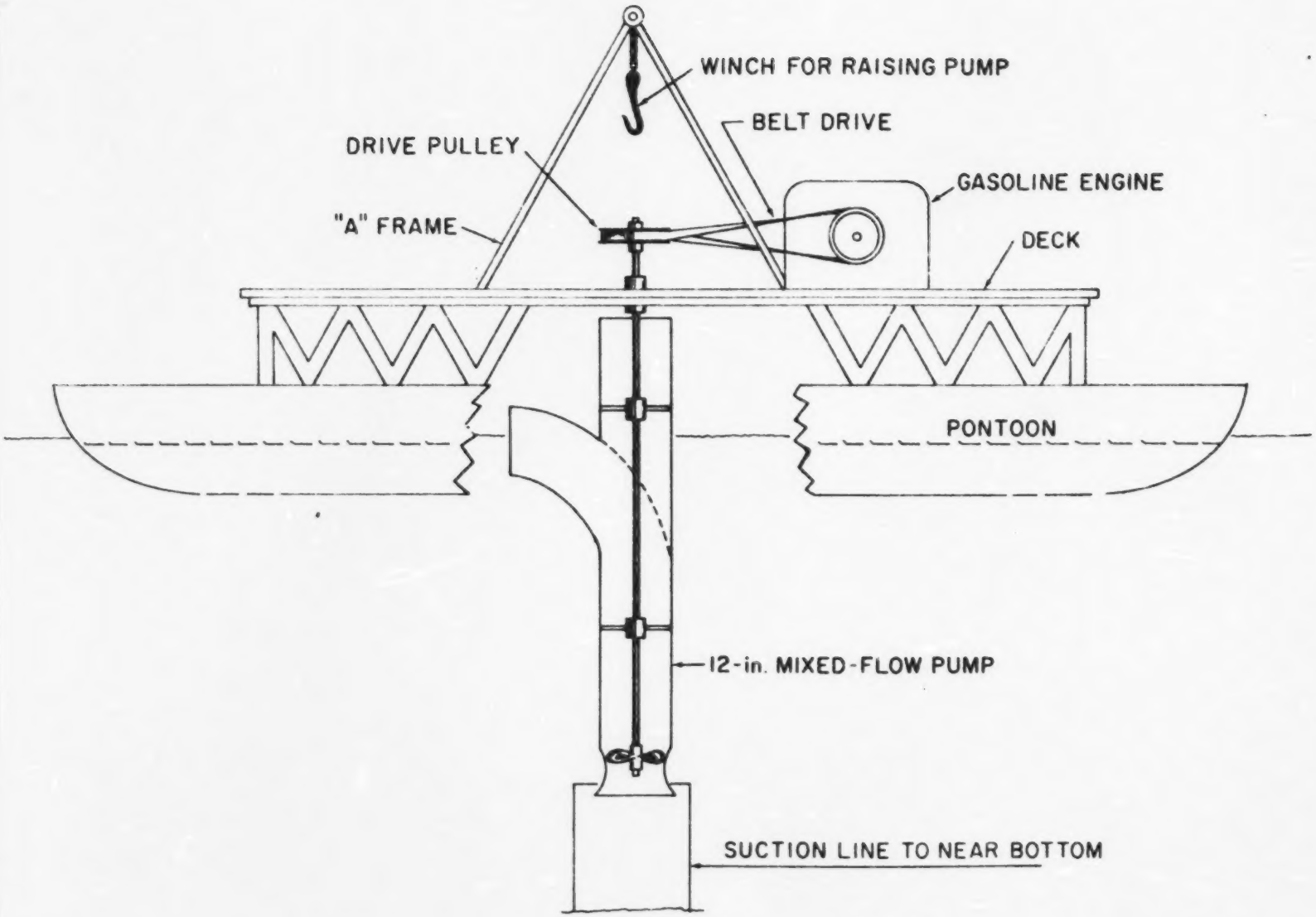


FIGURE 4. DESIGN OF PUMP, PONTOON, AND MOTOR FOR DESTRATIFICATION.

This apparatus was placed on Boltz Lake in the northern part of the State of Kentucky. The lake had a surface area of about 100 acres and a volume of about 2,900 ac-ft. Bullock Pen Lake had relatively similar size and shape, 140 surface acres and about 3,200 ac-ft volume, and was a few miles from Boltz Lake and was chosen as a control on the experiment. Important water quality parameters were measured weekly at various depths at the pump site in the test lake and near the dam in the control lake throughout the summer of 1965. A comparison of the progression of these parameters in the test and control lakes before the mixing of the test lake began in August 1965, showed that the two lakes were behaving in similar fashion.

The test lake was artificially destratified by pumping bottom water to the surface for 5 weeks during August and early September 1965. This artificial destratification improved the water quality in the test lake as shown in Figures 5, 6, 7, and 8. Figure 5 shows that the lower water was warmed in the test lake, Figure 6 shows that DO was present at all depths, Figure 7 shows that the DO added to the test lake oxidized the sulfides that were originally present, and Figure 8 shows that the DO added to the test lake oxidized the manganese and caused its precipitation.

In addition, nutrient levels and algal populations were checked in the test and control lakes and these data showed that nutrients were not brought to the surface in large amounts in the test lake by mixing, and the algal population was not increased. Finally, temperature data taken at several places in the lake showed that the water movement pattern proposed in Figure 3 was true, and the lake could be completely mixed from one location. Details of this and the 1964 experiences with this apparatus, are

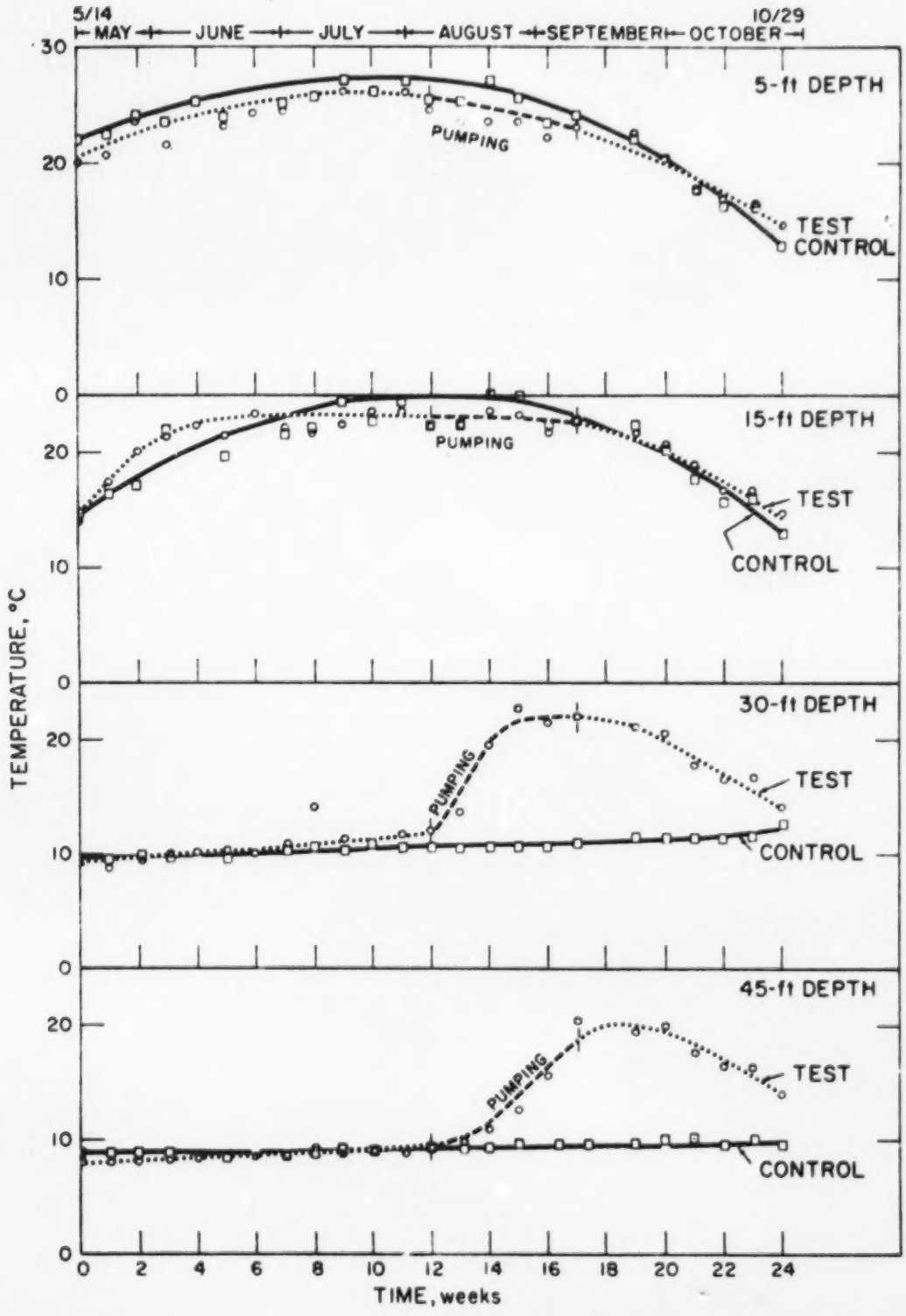


FIGURE 5. COMPARISON OF CHANGES IN TEMPERATURE WITH TIME AT FOUR DEPTHS IN TEST AND CONTROL LAKES

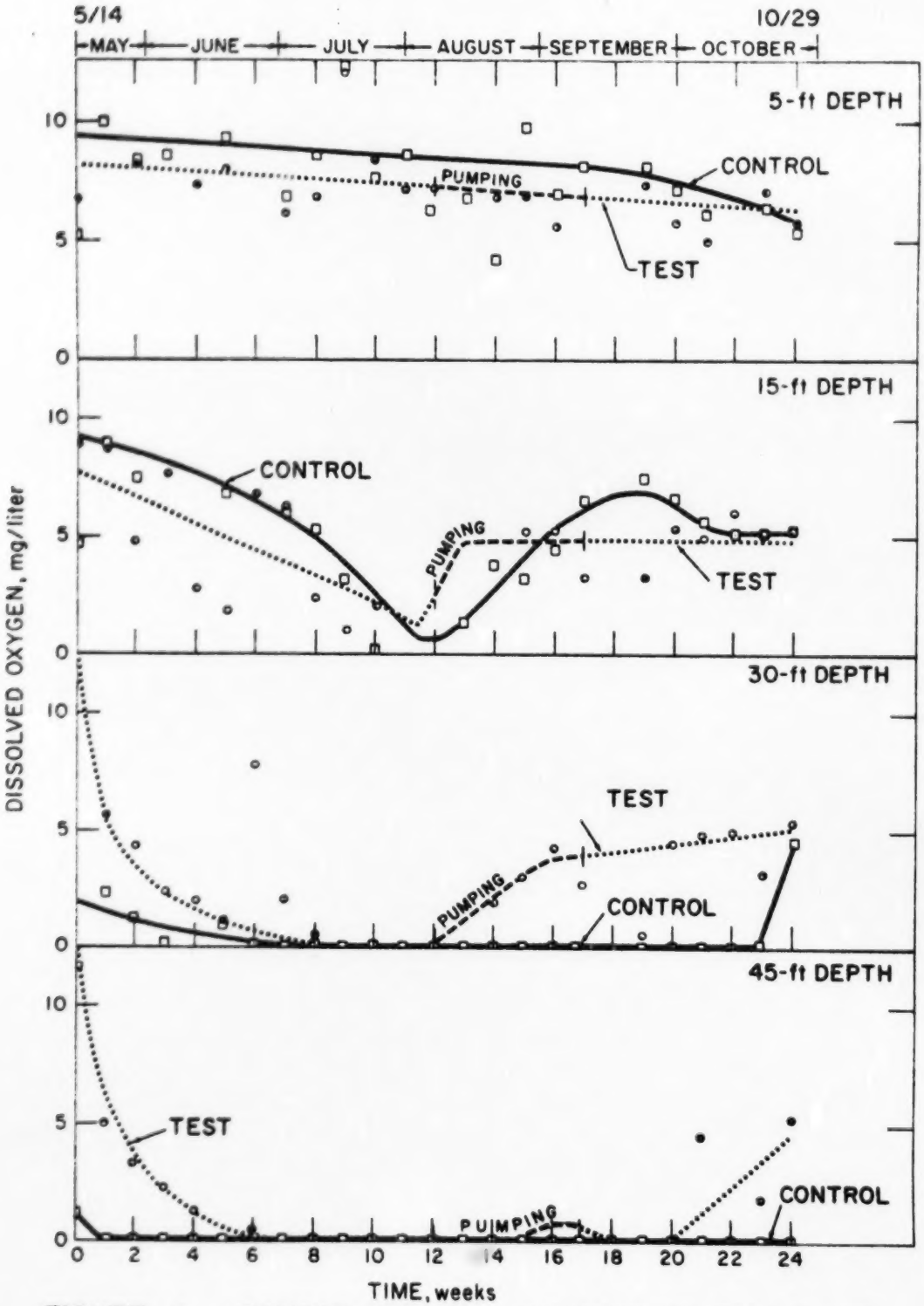


FIGURE 6. COMPARISON OF CHANGES IN DISSOLVED OXYGEN CONCENTRATION WITH TIME AT FOUR DEPTHS IN TEST AND CONTROL LAKES

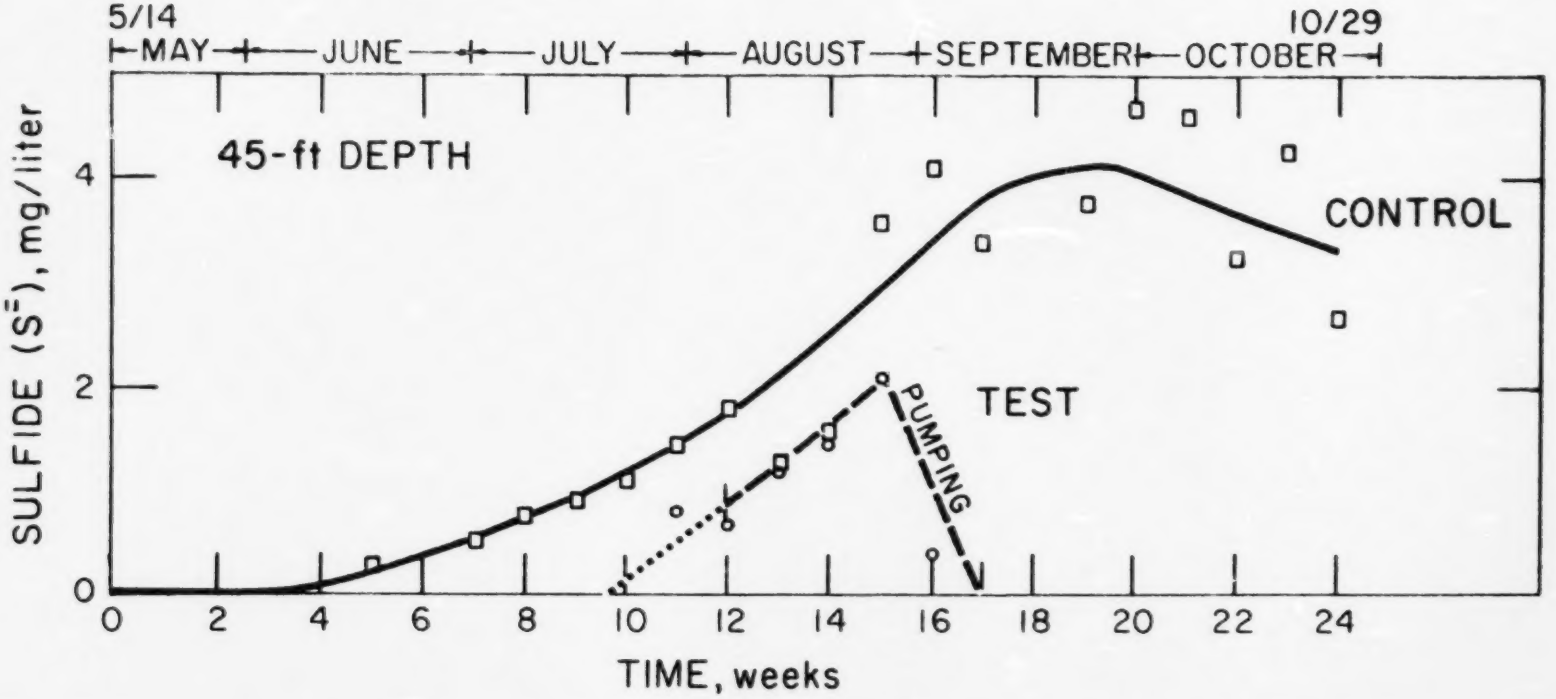


FIGURE 7. COMPARISON OF CHANGES IN SULFIDE CONCENTRATION WITH TIME AT 45-FOOT DEPTH IN TEST AND CONTROL LAKES

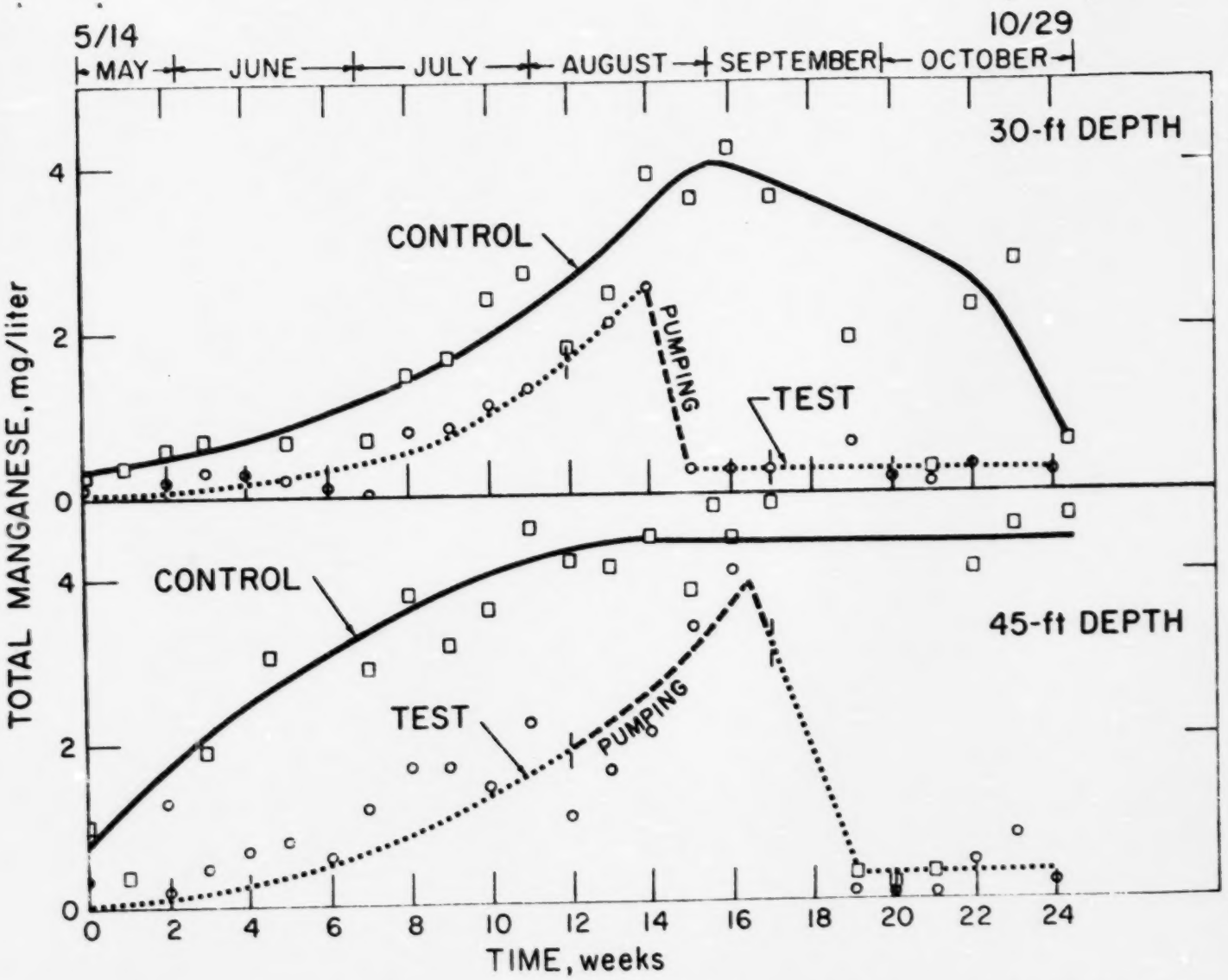


FIGURE 8. COMPARISON OF CHANGES IN TOTAL MANGANESE CONCENTRATION WITH TIME AT TWO DEPTHS IN TEST AND CONTROL LAKES

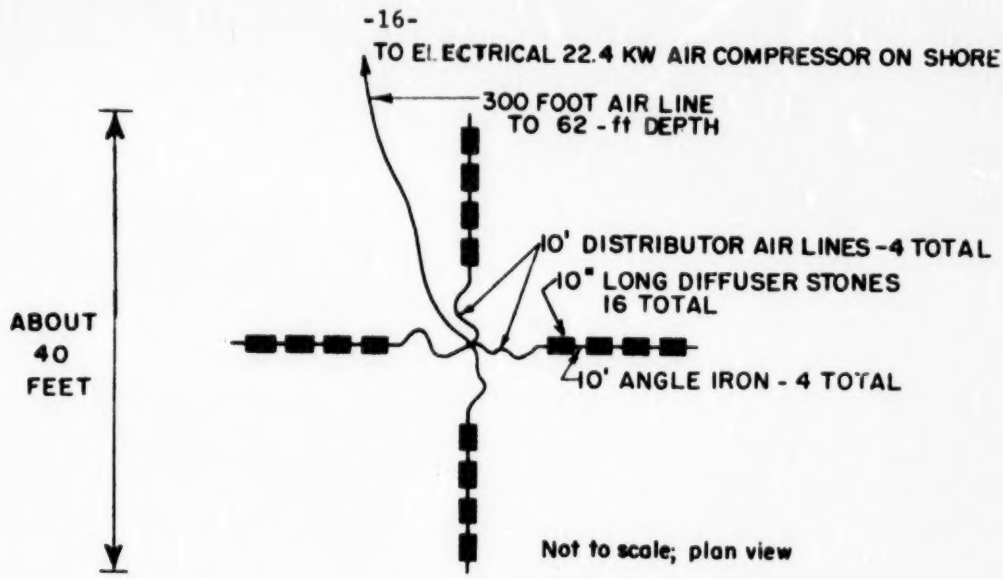
given[8,9,10] . A nearly complete bibliography on artificial destratification attempts is available.[10]

Artificial Destratification by Diffused-Air Pumping

While the pumping operation described was effective in destratifying the test lake and improving its water quality, the energy input per unit volume was somewhat higher than originally expected. In an effort to provide the same improvement in water quality, with reduced energy input, the same test lake was artificially destratified using a diffused-air pump during the spring and summer of 1966.

The equipment used for this operation was a 23-kw-hr portable air compressor that delivered 112 cfm at about 30 to 40 psi. The air was released through 16 porous ceramic diffusers spaced at 3-ft intervals in a cross pattern. This gave a cylinder of rising air approximately 40 feet in diameter which increased to about 100 feet diameter at the surface. Figure 9 shows a schematic diagram of this equipment. In addition to testing whether this new method would be more effective, the 1966 destratification was started in the spring rather than in midsummer, in an attempt to maintain good quality throughout a summer season rather than to improve water quality in midseason.[11]

The upper two parts of Figure 10 show the rising and falling pattern of the water temperature in the unmixed lake at the 5-foot depth during 1965 and 1966. Thermal stratification of lakes in the Northern Kentucky area is shown by the low and relatively constant temperature that persisted throughout the summer season at the depth that is 0.7 of the lake's maximum depth. Temperatures at this depth were the same as temperatures at the maximum depth.


TO ELECTRICAL 22.4 KW AIR COMPRESSOR ON SHORE
300 FOOT AIR LINE
TO 62 - ft DEPTH
10' DISTRIBUTOR AIR LINES - 4 TOTAL
10" LONG DIFFUSER STONES
16 TOTAL
10' ANGLE IRON - 4 TOTAL
ABOUT
40
FEET
Not to scale; plan view

DIFFUSED-AIR SYSTEM USED IN 1966

FIGURE 9. SCHEMATIC DIAGRAM OF THE DIFFUSED-AIR PUMP

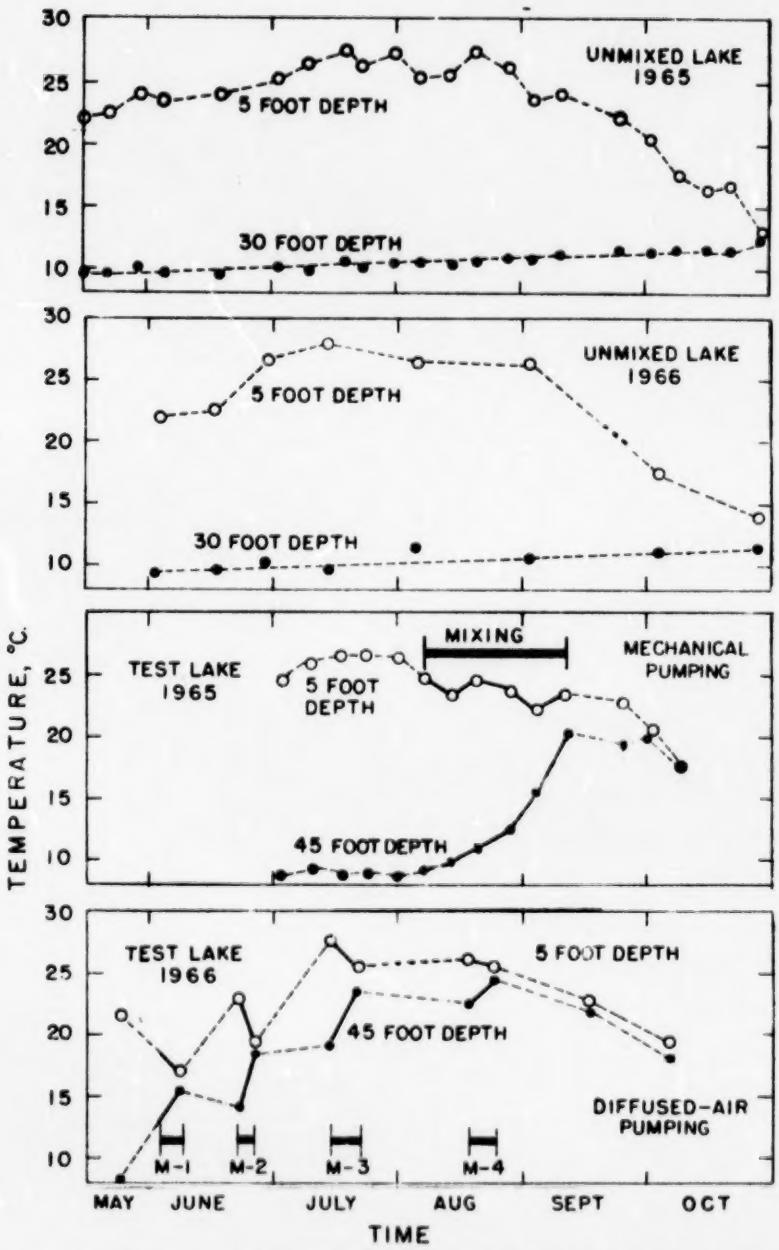


Figure 10. COMPARISON OF TEMPERATURE AT THE FIVE FOOT AND 0.7 DEPTH IN THE TWO STUDY LAKES.
(-----NO MIXING; ——MIXING)

For the unmixed lake this 0.7-depth is the 30-ft depth. Complete fall circulation is shown at the end of October in 1965 when the 5-ft and 30-ft temperatures became the same. In 1966, complete fall circulation occurred in mid-November, as shown by the 2.5°C difference in the upper and lower temperatures at the end of October.

The center portion of Figure 10, included for comparison purposes, shows the increase in temperature at the 0.7-depth (same as bottom temperature) in the test lake during mixing with the mechanical pump. At this time, there was a slight decline in surface water temperature. Thermal stratification was largely, but not completely, eliminated in the test lake during the 5-week mixing period. The lower portion of Figure 10 contrasts the temperature behavior at the 5-ft depth and the 0.7-depth in the test lake during 1966 when diffused-air pumping and multiple mixing techniques were used. In every case, mixing caused a sharp temperature rise in the lower waters, and some temperature decline in the surface water. Any decline in surface water temperature that occurs during artificial destratification would retard evaporation.

As in 1965, mixing in 1966 added DO to the water and oxidized any reduced substances present, therefore, these data are not repeated. Some information on phytoplankton will be given. Phytoplankton populations in the unmixed lake during 1965 (top portion Figure 11) rose in the early summer and then maintained a concentration of approximately 2,000 to 3,000 organisms per ml throughout the summer season. Similar data in 1966 were somewhat more erratic, but generally the counts were lower than in 1965. The lower portion of Figure 11 shows that at the 5-ft depth in the test lake, the counts declined both years during all of the mixing periods except one.

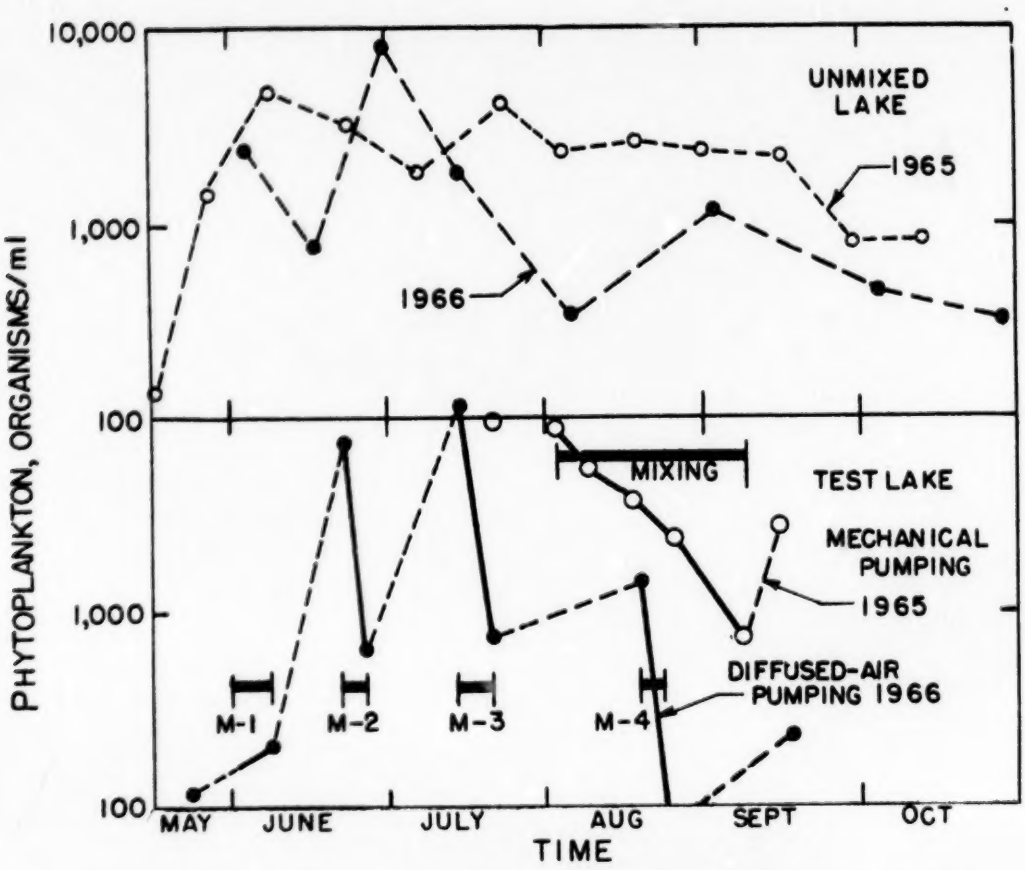


Figure 11. PHYTOPLANKTON COUNTS AT THE FIVE FOOT DEPTH IN THE TWO STUDY LAKES
(------NO MIXING,——MIXING)

The reason for the decline in phytoplankton populations at this time (1967) is not known. Possibly the rapidly altered environment was unfavorable to the algal population. Previous studies[9] indicated that surface clarity was not impaired during mixing. Whatever the reason, the effect of mixing was only temporary, as in every case after mixing stopped, the phytoplankton populations rose again.

Evaluation of Performance

Because mechanical equipment is used for artificial destratification some method is needed to design the most effective apparatus. Calculation of the "Oxygenation Capacity" and "Destratification Efficiency" as defined by Equations (1) and (2) is recommended.

$$\text{Oxygenation Capacity (OC)} = \frac{\text{Net Change in Oxygen Balance from } t_1 \text{ to } t_2}{\text{Total Energy Input from } t_1 \text{ to } t_2}$$

Where: t_1 = time of start of mixing

t_2 = time of end of mixing

The units of OC are pounds of DO transferred per kw-hr.

$$\text{Destratification Efficiency (DE)} = \left(\frac{\text{Net Change of Stability from } t_1 \text{ to } t_2}{\text{Total Energy Input from } t_1 \text{ to } t_2} \right) \times 100 \qquad (2)$$

Where: t_1 = time of start of mixing

t_2 = time of end of mixing

Stability = Energy needed to mix the lake[11]

Because the important effect of destratification is improvement of water quality, these parameters alone cannot be used to judge equipment[10,12], but they do give some guidelines for evaluation of performance.

SUMMARY AND CONCLUSIONS

Because the temperature of municipal drinking water is not limited in the United States, as it is in the Federal Republic of Germany[13], complete circulation of raw water reservoirs is permissible. The results of the experiments reported herein show that artificial destratification, while not the only engineering technique for water quality control, improves water quality in many ways and does not significantly worsen it in any way. Also, maintenance of good quality water by periodic mixing is better than one mixing.

The following specific conclusions can be made from the results of this study:

1. Bringing hypolimnion water to the surface of a reservoir with a mechanical- or diffused-air pump will eliminate thermal stratification.

2. Artificial destratificaton adds DO to the water and oxidizes any reduced substances.

3. Phytoplankton populations are not increased during reservoir mixing.

4. Reservoir water quality control should begin in the spring or early summer and should be continued throughout the summer to prevent any quality deterioration.

5. Mechanical performance may be judged by the calculation of the "Oxygenation Capacity" and "Destratification Efficiency," as defined herein.

ACKNOWLEDGMENTS

The authors express their sincere appreciation to the following members of the Engineering Activities staff who helped collect the data upon which this paper was based: Messrs. Lawrence J. Kamphake, Ernest L. Robinson, George Holtzer, Richard T. Shibiya, and Glenn R. Gruber. In addition, acknowledgment is made of the cooperation of the personnel of the State of Kentucky's Department of Fish and Wildlife Resources for their help with these studies. Finally, the authors are especially grateful to Dr. H. Bernhardt of the Wahnbachtalsperronverband, Siegburg, Federal Republic of Germany for translating and preparing this paper for publication.

BIBLIOGRAPHY

1. Ingols, R.S., "Pollutional Effects of Hydraulic Power Generation," Sewage and Industrial Wastes, 29, 292-297 (1957).

2. Ingols, R.S., "Effects of Impoundment on Downstream Water Quality, Catawba River," Journal American Water Works Association, 51, 42-46 (1959).

3. Fish, F. F., "Effect of Impoundment on Downstream Water Quality, Roanoke River, N.C." Journal American Water Works Association, 51, 47-50 (1959).

4. Churchill, M.A., "Effects of Storage Impoundments on Water Quality," Journal Sanitary Engineering Division, American Society of Civil Engineers, 83, SA-1, Paper No. 1171 (1957).

5. Love, S.K., "Relationship of Impoundments to Water Quality," Journal American Water Works Association, 53, 559-568 (1961).

6. Woodward, R.L., and LeBosquet, M., "Effects of Reservoir Operation on Stream Water Quality," Public Health Reports, 64, 1223-1229, (September 30, 1949).

7. Kittrell, F.W., "Thermal Stratification in Reservoir," Symposium on Streamflow Regulation for Quality Control, Robert A. Taft Sanitary Engineering Center, PHS Publ.. No. 999-WP-30, p. 57-67 (June 1965).

8. Irwin, W.H., Symons, J.M. and Robeck, G.G. "Impoundment Destratification by Mechanical Pumping," Journal Sanitary Engineering Division, American Society of Civil Engineers, 92, SA-6, 21-40 (Dec. 1966).

9. Symons, J.M., Irwin, W.H., and Robeck, G.G., "Impoundment Water Quality Changes Caused by Mixing," Journal Sanitary Engineering Division, American Society of Civil Engineers, 93, SA-2 (April 1967).

10. Symons, J.M., Irwin, W.H., Clark, R.M., and Robeck, G.G., "Management and Measurement of 'DO' in Impoundments," Journal Sanitary Engineering Division, American Society of Civil Engineers, In Press.

11. Schmidt, W., "Ueber den Energiegehatt der Seen, mit Biespielen vom Lunzer Untersee nach Messngen mit einem einfachen Temperaturlot," Internat. Rev. ges. Hydrobiologie u. Hydrographie, Hydrog. Supp. No. 1, 6, 1-25 (1913).

12. Symons, J.M., Irwin, W.H., Robinson, E.L. and Robeck, G.G., "Impoundment Destratification for Raw Water Quality Control by Either Mechanical- or Diffused-Air Pumping," Journal American Water Works Association, In Press.

13. Bernhardt, H., "Aeration of the Wahnbach Reservoir Without Changing the Temperature Profile," Journal American Water Works Association, 59, No. 8, 943-964 (Aug. 1967).